Permalloy, A New Magnetic Material of Very High Permeability

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SYNOPSIS: The magnetic alloy described in this paper is a composition of about 78.5% nickel and 21.5% iron and at magnetizing fields in the neighborhood of .04 gauss and with proper treatment has a permeability running as high as 90,000. This is about 200 times as great as the permeability of the best iron for these low magnetizing fields. This high permeability is attendant upon proper heat treatment and also upon other factors among which is freedom from elastic strain. The presence of other elements than iron or nickel and specially carbon, reduces the permeability, but slight variations in heat treatment produce large changes compared with those due to small quantities of impurities.

So far as discovered, other physical properties show no peculiarities at the composition which brings out the remarkable magnetic properties of permalloy. The equilibrium diagram, electric conductivity, crystal structure, mean spacing between adjacent atom centers and density are among the physical properties which have been studied.

To the engineer in electrical communication the development of permalloy is very significant. It assures a revolutionary change in submarine cable construction and operation and promises equally important advances in other fields.—*Editor.*

SOME time ago it was discovered in the Bell System laboratory[1] that certain nickel-iron alloys, when properly heat-treated, possess remarkable magnetic properties. These properties are developed in alloys which contain more than 30 per cent of nickel and which have the face-centered cubic arrangement characteristic of nickel crystals, rather than the body-centered structure characteristic of iron. The entire range above 30 per cent nickel exhibits these properties to some degree and offers new possibilities to those interested in magnetic materials. The most startling results, however, are obtained with alloys of approximately 80 per cent nickel and 20 per cent iron, whose permeabilities at small field strengths are many times greater than any hitherto known. To alloys of this approximate composition we have given the name "permalloy". The development of permalloy has assured us a revolutionary change in submarine cable construction and operation, and promises equally important advances in other fields of usefulness. It also presents questions of great interest to the scientist, and emphasizes again the meagreness of our fundamental information about ferromagnetism. The present paper is intended to give a general discussion of the preparation and testing of permalloy, with sufficient detail to indicate its unusual characteristics. Detailed statements of numerical results are reserved for publication in separate articles dealing with specific properties.[2]

[1]British Patent No. 188,688.

[2]L. W. McKeehan, The Crystal Structure of Iron-Nickel Alloys, Phys. Rev. (2), 21, (1923).

In making permalloy we use the purest commercial nickel and Armco iron. Our samples for laboratory study are prepared by melting these metals in a silica crucible, using a Northrup high-frequency induction furnace. The particular furnace which we use will conveniently melt a charge of about six pounds. An analysis typical of the resulting billets is as follows:

Ni	78.23
Fe	21.35
C	.04
Si	.03
P	trace
S	.035
Mu	.22
Co	.37
Cu	.10

The presence of other elements than nickel and iron is of course to be expected after any practical method of preparation. To determine their effects, samples were prepared in which the usual impurities were present in various proportions. It was found that their presence does affect the permeability of the alloys and that carbon is especially harmful. Since, however, the variations produced by slight changes in heat-treatment are very large compared with those due to small quantities of impurities we have found it unnecessary for most purposes to require higher purity than that indicated in the analysis above given.

In our laboratory studies we have made it a practice to reduce the billets through the forms of rod and wire to tape 3.2 mm. wide and 0.15 mm. thick. Accordingly test samples are available in a variety of forms and conditions. Thin narrow tape is particularly adapted to use in experiments involving heat-treatment, since it possesses a high ratio of area to volume and is easy to manipulate. Fortunately the entire nickel-iron series can be mechanically worked if sufficient care is exercised and we have thus been able to use samples of the same size, shape, and mechanical condition in all measurements upon which we have based comparisons between alloys. This practice has also made possible strictly comparable micrographic studies throughout the series.

Permeability is the magnetic characteristic of permalloy in which we first became interested and we have used its numerical value as an index in establishing the effects of mechanical and thermal treatments. Most of the measurements have been made in a ring permeameter of special design. The ring sample is prepared by winding twenty or more turns of tape around a disk about three inches in diameter. The disk is then removed leaving the material in the form of a spirally laminated ring with a rectangular cross-section approximately 3.2 mm. by 6 mm. A single massive copper conductor is linked with this ring, and constitutes also the secondary of a transformer whose primary winding forms one arm of an inductance bridge. From the bridge measurements, and the dimensions of the ring the permeability of the latter may readily be computed. For most of the measurements 112-cycle alternating current has been employed, permitting the use of telephone receivers in adjusting the balance of the bridge. The ring is sufficiently well laminated so that no serious troubles are introduced at this frequency by eddy currents. This fact was verified by making a number of permeability determinations at alternating current frequencies both above and below that chosen for routine use, and also by comparing the results of ring permeameter tests with those of ballistic tests on specially wound ring samples. The bridge method is particularly well adapted to the measurement of permeability in very weak magnetic fields since amplifiers may readily be used to increase the delicacy of the bridge adjustment to almost any degree desired. As a matter of convenience we have usually included in our test program measurements with fields of 0.002, 0.003, and 0.010 gauss, and on the graph of permeability against magnetizing field strength the straight line through these points has been extended to field strength zero. We have called the permeability read from the graph at this point the "initial permeability" of the sample.

The form of permeameter used is especially adapted to making measurements quickly and with minimum handling of the sample, since it makes use of but a single magnetizing turn. The ring is laid on suitable insulating supports in an annular copper trough, and placing the copper cover on this trough completes the electrical circuit. In a modified instrument, the "hot permeameter", provided with a heating device, permeabilities may be measured from liquid air temperatures up to about 1000°C. without altering the position of the sample.

The heat-treatment of permalloy is of the utmost importance. To develop its maximum initial permeability it must be cooled not only through the proper temperature ranges, but also at the proper rates.

It is obvious that only a small part of any sample can be given the most favorable treatment, since the interior portions of the sample cool at rates which are dependent upon the geometrical configuration and thermal properties of the material and are only indirectly under the control of the experimenter. For these reasons each shape and size of sample will have its own best heat-treatment and it is obviously difficult to establish the correct heat-treatment for a small element of volume, characteristic of permalloy as a material. By the use of thin tape, however, we secure fairly uniform treatment of the whole volume so long as the cooling is not too rapid, and fortunately the best cooling rate is not much different from the normal cooling rate of the tape in the open air. It has been found that temperature changes below 300°C. have very little effect upon the resultant properties of permalloy, but the rate of cooling from just above the magnetic transformation temperature down to about 300°C. is a controlling factor. By a long series of experiments a heat-treatment has been established which is especially well adapted to the permalloy test rings already described. They are first heated at about 900°C. for an hour and allowed to cool slowly, being protected from oxidation throughout these processes. They are then reheated to 600°C., quickly removed from the furnace and laid upon a copper plate which is at room temperature.

Not only does each size and shape of sample require its own special heat-treatment, but samples differing only in composition also differ in their most suitable heat-treatments. In our investigation of the nickel-iron series we have not, however, attempted to determine the best heat-treatment for ring samples of each of the many alloys studied. By careful exploration we located the region about 80 per cent nickel, 20 per cent iron as the one promising the highest initial permeability and established the best heat-treatment for this composition. Keeping this treatment unchanged we then relocated the best composition, finding it to be at about 78.5 per cent nickel, 21.5 per cent iron. There is a maximum temperature in the equilibrium diagram for this binary at about 70 per cent nickel,[3] and it was natural to suspect that the maximum in initial permeability which we had found at 78.5 nickel might be displaced to 70 nickel by proper treatment. The 70 per cent nickel alloy was accordingly subjected to a great variety of heat-treatments, but no method was found capable of producing in it an initial permeability as high as that readily obtainable in the 78.5 per cent nickel alloy.

Fig. 1 shows the general way in which initial permeability has been found to vary throughout the nickel-iron series when the heat-treat-

[3]Bureau of Standards Circular No. 58, April 4, 1916.

ment determined as best for the 80 per cent nickel alloy is used. It is obvious from what has been said above that too much weight must not be given to the actual values recorded at any composition. Had the best heat-treatment been determined for each sample the curve might have been altered considerably in detail, particularly outside the permalloy range. We believe, however, that its general form is

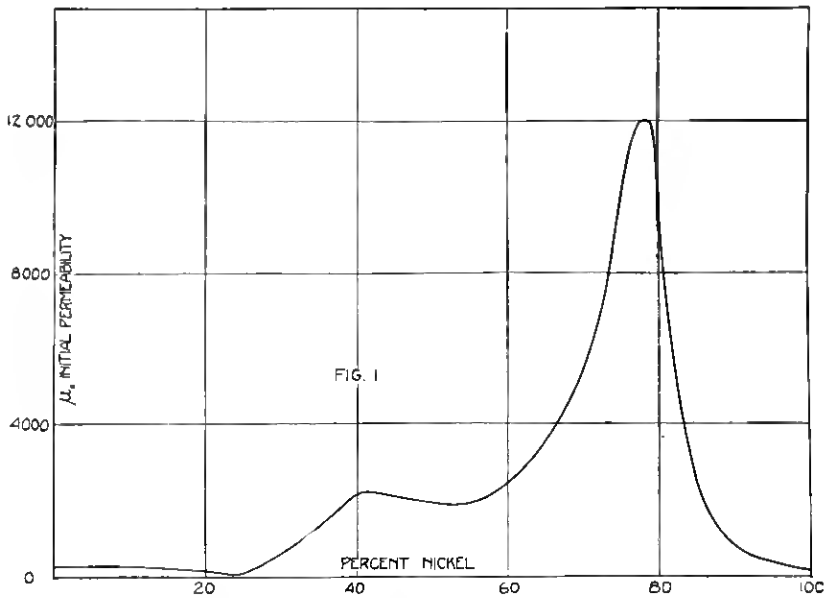

Fig. 1

approximately correct. Alloys were made at 5 per cent steps throughout the range except in the vicinity of 80 per cent nickel where a great number of slightly different compositions were investigated. The chemical analysis, rather than the intended composition, was used in every case, although the difference was never considerable.

The largest value of initial permeability for permalloy at room temperature which we have so far found in the ring permeameter is about 13000, more than 30 times the corresponding value for the best soft iron. How extraordinary this is may be appreciated by considering that this material, although it has a saturation value of magnetic intensity comparable with that of iron, approaches magnetic saturation in the earth's field. Unusual caution must therefore be exercised in measuring the properties of permalloy to protect the sample from the influence of stray magnetic fields. Fig. 2 shows, to

different scales, the values of initial permeability in similar ring samples of permalloy and of annealed armco iron, and small portions of the corresponding μ-H curves from which these were obtained.

We have measured the magnetization of permalloy at saturation and find that it is not sensitive to heat-treatment. The saturation values of magnetization per gramatom are known to vary almost

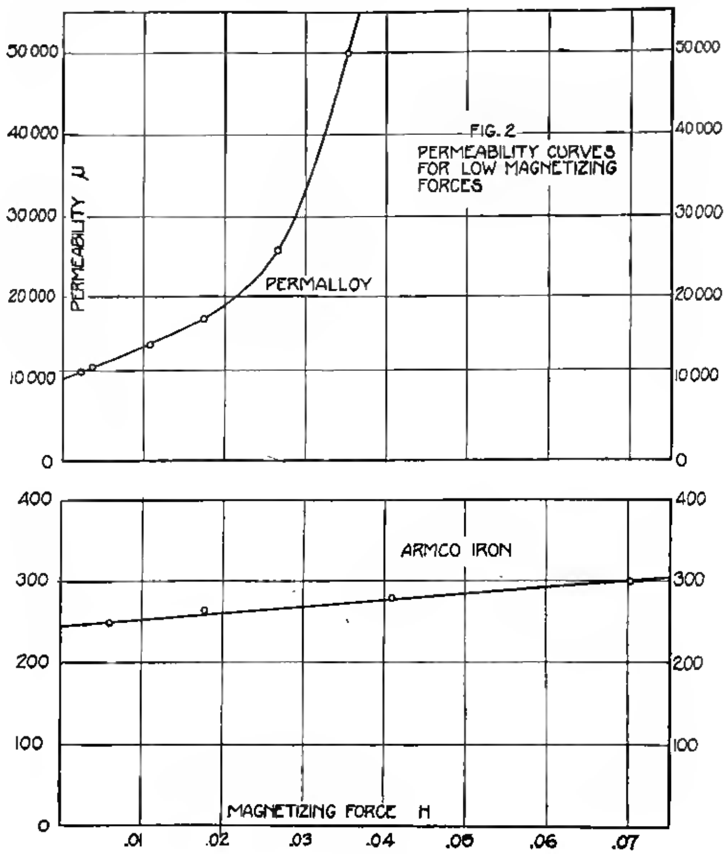

Fig. 2

linearly with composition throughout the nickel-iron series, from 222 for iron to 59 for nickel.[4] The value 84 which we have found for the 78.5 per cent nickel alloy is therefore not abnormal.

The magnetic characteristics of heat-treated ring samples of the same alloy have also been determined through a wider range of field

[4] P. Weiss, Faraday Society Trans. 8, 149-156 (1912).

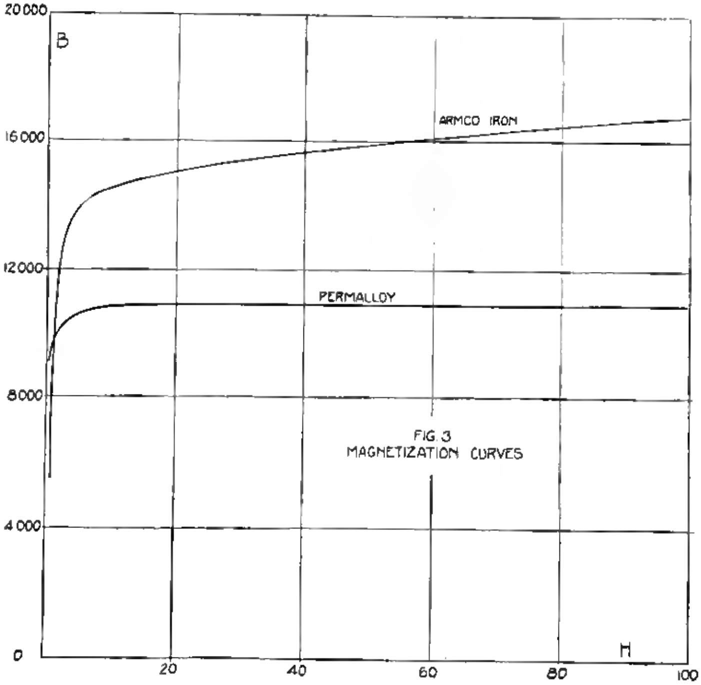
20000
B
ARMCO IRON
16000
12000
PERMALLOY
8000
FIG. 3
MAGNETIZATION CURVES
4000
0
H
20
40
60
80
100

Fig. 3

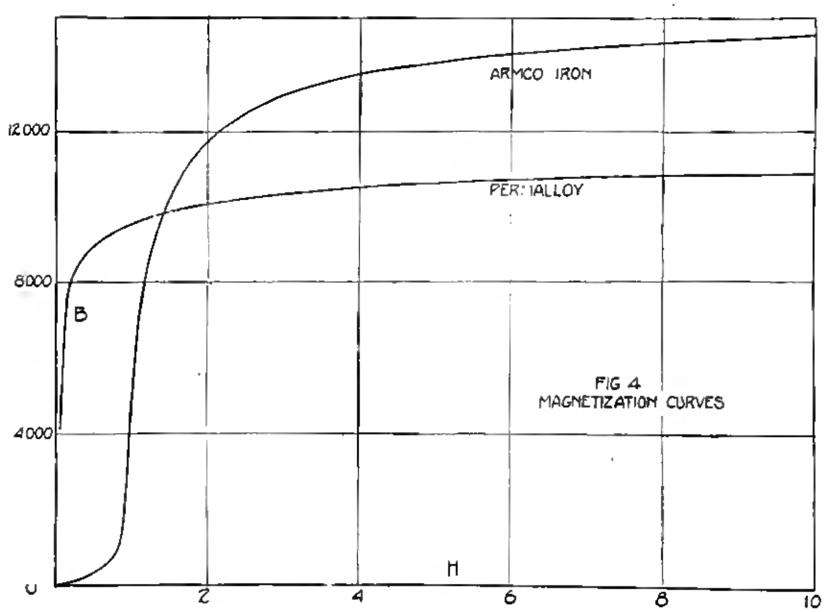
ARMCO IRON
12000
PERMALLOY
8000
B
FIG 4
MAGNETIZATION CURVES
4000
H
2
4
6
8
10

Fig. 4

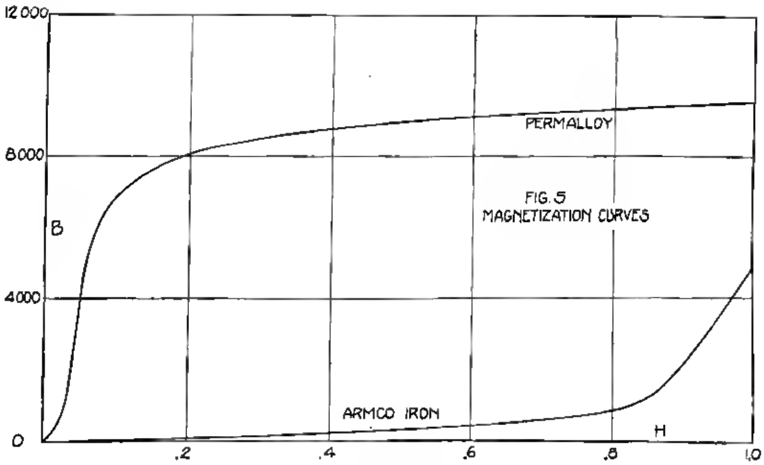
12000
8000
4000
0
B
PERMALLOY
FIG. 5
MAGNETIZATION CURVES
ARMCO IRON
H
.2
.4
.6
.8
1.0

Fig. 5

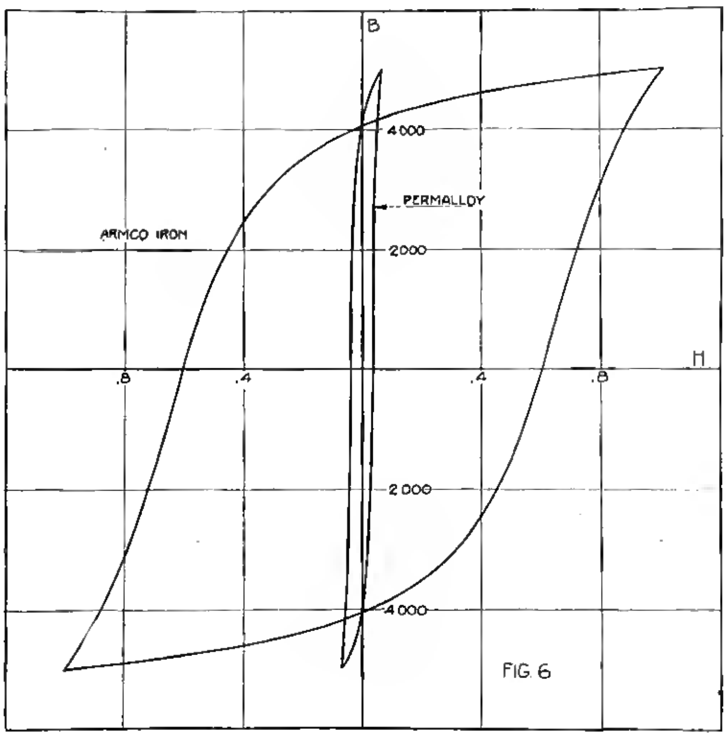
B
4000
PERMALLOY
ARMCO IRON
2000
H
.8
.4
.4
.8
2000
4000
FIG. 6

Fig. 6

strengths by ballistic methods. Figs. 3, 4, and 5 show B-H curves for such a sample of permalloy and for a sample of annealed armco iron. From Fig. 5 is apparent the enormous susceptibility of the former material in the weak fields so important in communication engineering. Fig. 6 shows for the same two materials hysteresis loops carried to a maximum induction of 5000 maxwells. The area of the permalloy loop is only one sixteenth that of the loop for soft iron. Fig. 7 shows

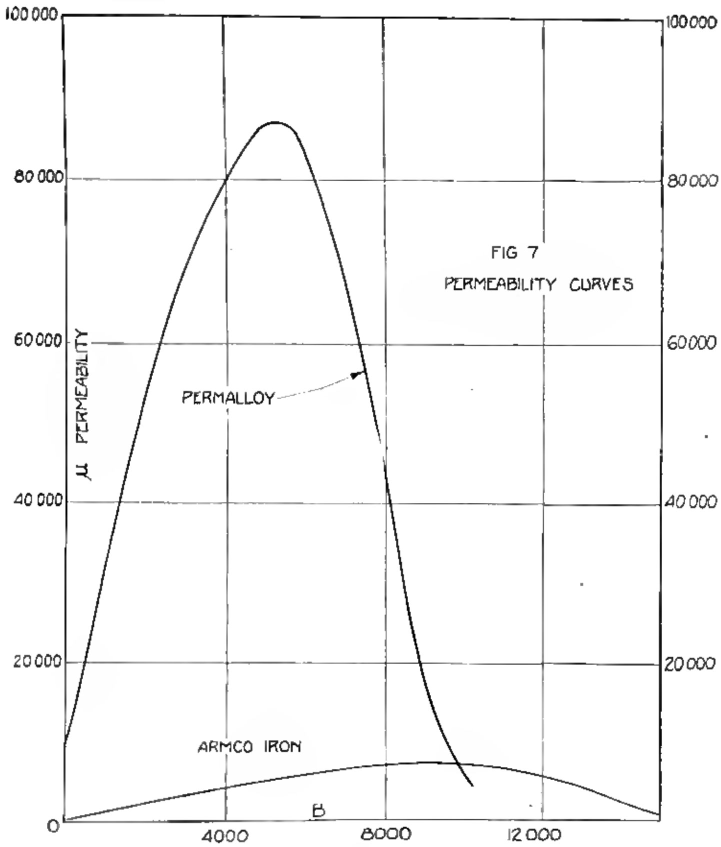

Fig. 7

the μ-B curves for these materials. The maximum permeability here shown, $\mu = 87000$, which is not exceptionally high for permalloy largely exceeds the highest values obtainable in silicon steel[5] and of course occurs at a much lower flux density.

[5]T. D. Yensen, U. S. Patent 1,358,810.

Early in the investigations it was found that heat-treated permalloy is sensitive to strain, and the routine measurements were so conducted as to avoid this disturbing effect. Separate investigations of the effects of strain upon permeability and electrical conductivity in straight samples, and of the converse effects of magnetization upon dimensions and conductivity were also undertaken. While these studies are not yet complete it can be stated that all these effects are large in comparison with the corresponding effects in hitherto available magnetic materials. So long as the elastic limit of the material is not exceeded the effects due to strain are reproducible and disappear when the strain is relieved. The effects of magnetization, however, show the expected hysteretic properties. As an example of the magnitude of the effects producible it may be stated that between its value in the unstrained condition and about one-tenth that value the initial permeability of a heat-treated strip of certain of these materials can, by the mere variation of strain, be adjusted to any value we may for the moment desire. The range through which the conductivity can similarly be adjusted by strain is much narrower, the maximum reduction being about 2 per cent, which, however, is a large effect compared with that found in other metals.

The effect of magnetization in reducing conductivity is as much as 2 per cent for fields of the order of one gauss. This makes it easy, for example, to measure the earth's magnetic field to within about 1 per cent by finding the strength of the opposing field necessary to give a permalloy strip its maximum conductivity. It will be noted that the conductivity change which we have mentioned as attainable by magnetization is the same as that attainable by elastic strain. This is no mere coincidence, for we find that the maximum change due to either cause alone is not further increased by superposition of the other, although the effects of small tensions and magnetizing fields are additive. This suggests, of course, that both causes ultimately produce the same change in the mechanism responsible for conduction.

Since the effect of tension upon permeability is in some of these cases so marked it seemed surprising that the only reported study[6] of the converse effect, that is of magnetostriction, indicated a zero value within the permalloy range. It appeared advisable therefore to study the magnetostriction of the series of alloys here available. Preliminary results indicate that under usual conditions of experiment, heat-treated 78.5 per cent nickel alloy exhibits larger magnetostriction than does iron.

[6]K. Honda and K. Kido, Tohoku Univ. Sci. Rep., 9, 221-232, (1920). It should be noted, however, that their alloys had received different treatments than ours.

With the remarkable ferromagnetic behavior of permalloy in mind one naturally looks for analogous peculiarities in its other properties. As has been shown, however, the equilibrium diagram does not point accurately to the composition exhibiting highest initial permeability. The conductivity curve is even less indicative of a peculiarity at this point, its minimum lying at about 35 per cent nickel. The crystal structure is that of nickel and its type does not change until the nickel content is made less than 35 per cent. Even the mean spacing between adjacent atom-centers, and with it the density, varies continuously throughout the entire range. Our experience in working these alloys also indicates that the series has no mechanical peculiarities at or near 80 per cent nickel. Not only do these characteristics indicate no abnormality as the nickel content is increased beyond 70 per cent, but, what is more surprising they are little affected by the heat-treatments which so profoundly change the magnetic properties. So far as has been determined, therefore, it is only in connection with its magnetic properties that permalloy is unusual.

To the engineer the discovery of permalloy means the realization of plans long impossible of accomplishment for lack of a suitable material. For the scientist the principal interest in these materials may well lie in the large response of their magnetic properties to simple external controls. Without alteration of composition these properties may be adjusted through extraordinary ranges by strain, by magnetization, or by heat-treatment. This allows a more definite study of the way in which these factors are related to magnetic properties than has been possible with materials hitherto available in which their effects are comparatively small and may be associated with complicated and irreversible changes in other properties. The behavior of permalloy demonstrates that ferromagnetism is associated with material structure in a different way than are the ordinary physical and chemical properties and its extreme sensitiveness to control gives us a powerful method for use in magnetic investigations.